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COMPARISON OF ITTC-78 AND DTMB STANDARD SHIP PERFORMANCE PREDICTION METHODS

By
Kenneth M. Forgach

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NOTATION

The notation used in this document is consistent with the International Towing Tank Conference (ITTC) Symbols and Terminology List - Beta Version 1996, except where noted.

STANDARD SYMBOLS (Abbreviated List)

c	Propeller blade chord length at 0.75 r /R
C_A	Ship/Model Correlation Allowance (DTMB method)
C_D	Propeller blade drag coefficient
C_F	Frictional Resistance Coefficient (ITTC-78 Friction Line)
ΔC_F	ITTC-78 roughness allowance $= [105 \cdot (k_s / L)^{1/3} - 0.64] \cdot 10^{-3}$
C_N	Trial correction for propeller rate of revolution at speed identity (ITTC-78 method)
C_P	Trial correction for delivered power (ITTC-78 method)
C_R	Residuary Resistance Coefficient
C_T	Total Resistance Coefficient
C_V	Viscous Resistance Coefficient
C_W	Wavemaking Resistance Coefficient
D	Propeller Diameter
F_D	Towing Force- friction correction - in self propulsion test (DTMB method)
F_n	Froude Number
J	Propeller advance ratio $= V_A / (n D)$
J_A	Apparent or hull advance ratio $= V / (n D)$
J_T	Propeller advance ratio based on thrust identity (@ K_T)
k	Three dimensional form factor on flat plate friction (ITTC-78 method)
k_P	Propeller blade roughness - ship scale ($30 \cdot 10^{-6}$ m recommended - ITTC-78 method)
k_s	hull roughness ($150 \cdot 10^{-6}$ m recommended - ITTC-78 method)
K_Q	Torque Coefficient
K_{QT}	Propeller Torque Coefficient based on thrust identity (@ K_T)
K_T	Thrust Coefficient
L	Length
L_{WL}	Length on the waterline
m	used as a subscript denotes model scale
n	Propeller Rate of Revolution
n_T	Propeller Rate of revolution - corrected to specific ship trial conditions (ITTC-78 method)
P	Propeller blade pitch at 0.75 r/R
PD	Delivered Power at Propeller
PD_T	Delivered Power at Propeller corrected to specific trial conditions (ITTC-78 method)
PE	Effective Power (Resistance)
Q	Torque
R	Resistance (in general)
R_A	Towing Force - friction correction - in self propulsion test (ITTC-78 method)
R_I	Ideal resistance at self propulsion point during model propulsion test ($R_T - F_D$)
R_n	Reynolds number
R_{nco}	Propeller blade Reynolds number at 0.75 r/R

RPM	Propeller Rate of Revolution (r/min)
R_R	Residuary resistance
R_T	Total resistance
R_V	Viscous resistance
s	used as a subscript denotes ship scale
S	Wetted Surface
S_{BK}	Wetted surface of bilge keels - ship scale (ITTC-78 method)
t	Thrust Deduction Fraction
tb	maximum propeller blade thickness at 0.75 r/R
T	Thrust
V	Speed of hull
V_A	Propeller advance speed (equivalent propeller open water speed @ T or Q identity)
w_Q	Wake Fraction (torque identity)
w_T	Wake Fraction (thrust identity)
Z	number of propeller blades
Δ	Displacement
η	[Eta] Efficiency (in general)
η_D	Propulsive efficiency (PE/PD)
η_H	Hull efficiency
η_O	Propeller efficiency in open water
η_R	Relative rotative efficiency
λ	[Lamda] Model linear scale ratio
ν	[Nu] Kinematic Viscosity (ft^2/sec or m^2/sec)
ρ	[Rho] Water Mass Density (lb*sec^2/ft^4 or kg/m^3)

INTERNATIONAL SYSTEM OF UNITS (SI) CONVERSION FACTORS

U.S. CUSTOMARY	METRIC EQUIVALENT
1 inch	25.4 millimeter (mm), 0.0254 meter (m)
1 foot (ft)	0.3048 meter (m)
1 pound of force	0.4536 kilograms (kg)
1 foot - pound (ft - lb)	0.1382 kilogram - meter (kg - m)
1 foot per second (ft/s)	0.3048 meter per second (m/s)
1 knot	0.5144 meter per second (m/s)
1 degree of angle (deg)	0.01745 radians (rad)
1 horsepower (hP)	0.7457 kilowatts (kW)
1 long ton	1.016 tonnes, 1.016 metric tons, or 1016.0 kilograms
1 inch water (60°F)	248.8 pascals (pa)

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ABSTRACT

The standard ship performance prediction method used at the David Taylor Model Basin (DTMB) is compared to the method proposed by the 15th International Towing Tank Conference in 1978 (ITTC-78).

ADMINISTRATIVE INFORMATION

The report was written at the David Taylor Model Basin, Naval Surface Warfare Center, Carderock Division (NSWCCD), herein referred to as DTMB, by the Hydromechanics Directorate, Code 5200, under work unit number 4-5000-001.

INTRODUCTION

The methods by which model scale test data are extrapolated to predictions of full scale ship resistance and powering performance differ between model basins. Different extrapolation methods applied to the identical raw model data can yield ship delivered power predictions that can vary by five to ten percent. This makes it problematical to directly compare test results and predictions from different model basins; yet, it is often necessary to do so.

This report compares the standard ship performance prediction method used at the David Taylor Model Basin (DTMB) to the method that was proposed by the 15th International Towing Tank Conference in 1978 (ITTC-78). Although it is impractical to try to consider all the different extrapolation techniques in use, many tow tanks use elements of the ITTC-78 method.

This report is organized into 3 parts. In the main body of the report, the two different methods are described, compared and discussed. Following that are two appendices that show the details and all the intermediate results of the ITTC-78 and the DTMB standard ship performance prediction methods.

SUMMARY

The **DTMB standard ship performance prediction method** is a relatively simple procedure that directly extrapolates ship delivered power (PD) and shaft rotation rate (n) from model measurements made at the self propulsion point. The self propulsion point is defined so that the model and ship propeller thrust coefficients (K_T) and propeller efficiencies (η_O) are identical.

Underlying the DTMB powering prediction method are the assumptions that model and ship speed are Froude scaled and that the coefficient of residuary resistance (C_R), propeller efficiency (η_O) and overall propulsive efficiency (η_D) of the model are equal to that of the ship. In order to achieve equality between model and ship propeller efficiencies, the model is assisted during the

propulsion experiment with the application of the correct amount of tow force, F_D. This tow force can also be thought of as a model to ship friction correction. Because the ratio of viscous resistance to residuary resistance is larger for the model than for the ship at the same Froude scaled speed, a fully self propelled model would need to produce proportionally more propeller thrust than would the full scale ship and, therefore, the model propeller would be overloaded relative to the ship propeller. By applying the correct amount of tow force to the model during the propulsion experiment, the model propeller works against an "ideal" resistance (R_I) which is less than the actual or total model resistance (R_T) by the amount F_D. This technique of propelling the model at the "ship self propulsion point" rather than at the "model self propulsion point" results in equality between the model and ship propeller thrust coefficient which is necessary for identical model and ship propeller efficiencies.

The tow force, F_D, is, therefore, determined for each model speed so that the ratio of viscous to residuary resistance at the model scale is similar to that at the ship scale:

$$\frac{R_{Vm} - F_D}{R_{Rm}} = \frac{R_{Vs}}{R_{Rs}} .$$

Or, in a more directly applicable formula, the tow force required at the self propulsion point, as defined by the DTMB method, is simply the difference between the model and ship frictional resistance coefficients (C_F) and the ship-model correlation allowance, C_A:

$$F_D = 1/2\,(\rho\, S\, V^2)_m\,[C_{Fm} - (C_{Fs} + C_A)]$$

Model and ship frictional resistance coefficients are determined by the 1957 ITTC Friction Line. The appropriate C_A is generally selected from the Navy historical correlation data base. Ships in the data base are Navy combatants and auxiliaries and large commercial tankers. The individual correlation allowance data points are congruous with the DTMB method because they were determined through full scale standardization trials and model correlation experiments conducted according to this same standard DTMB method.

Thus, the predicted ship delivered power and propeller RPM are directly related to one another and are a function of a single adjustable parameter, C_A. No further attempts are made in the DTMB method to account for other viscous or form related effects, or to correct for scale effects such as differences between the model and ship wakes or differences between model and ship propeller performance.

In contrast, the **ITTC-78 performance prediction method** does attempt to account for these effects and so employs several adjustments or corrections. Accordingly, there are several

key differences between the ITTC-78 and DTMB methods in terms of both test and extrapolation technique.

The single most significant difference between the ITTC-78 and DTMB extrapolation methods is the use, by ITTC-78, of the form factor (k). Form factor represents the effect of the hullform on the total viscous resistance. It is a 3-dimensional form factor applied to flat plate friction:

$$k = (C_V - C_F) / C_F$$

where C_V represents the coefficient of total viscous resistance and C_F the coefficient of frictional resistance for a flat plate in 2-dimensional flow. With the use of form factor, residuary resistance may be separated into two components: wave making resistance, which scales as λ^3, and form drag, which is proportional to skin friction resistance.

$$C_R = C_W + k \cdot C_F$$

Form factor is usually determined experimentally by applying Prohaska's Method to low speed ($0.1<F_n<0.22$) bare hull model resistance data.

Form factor applied in the effective power (PE) extrapolation, results in a lower calculated value of the coefficient of residuary resistance (C_R) and therefore a lower value for the predicted ship scale coefficient of total resistance (C_{Ts}) and PE:

$$C_R = C_{Rm} = C_{Rs} = C_{Tm} - C_{Fm}\,(1+k)$$

$$C_{Ts} = C_R + C_{Fs}\,(1+k) + \Delta C_F$$

$$C_{Ts} = C_{Tm} + (C_{Fs} - C_{Fm})\,(1+k) + \Delta C_F \qquad \text{where } C_{Fs} < C_{Fm}$$

Form factor also influences the prediction of delivered power (PD) because it affects the definition of the self-propulsion point, appearing in the formula used to calculate the tow force (R_A) applied during the self-propulsion test:

$$R_A = 1/2\,(\rho\, S\, V^2)_m\,[1+k\,(C_{Fm} - C_{Fs}) - \Delta C_F\,]$$

Because form factor appears in this equation, the calculated value of tow force is greater than in the DTMB method. If a greater tow force is applied to the model, the measured values of model scale propeller shaft thrust, torque and RPM are less, and therefore, the predicted ship scale PD is less (than that predicted by the DTMB method). In other words, the ITTC-78 and DTMB extrapolation methods actually define different self propulsion points for the same test condition.

Although the use of form factor is the single most significant difference between the methods, there are other differences. Additional adjustments applied to the ITTC-78 propulsion test data, but not used in the DTMB method, include: a correction to the wake (w_T correction) to account for the relative size of the boundary layer between the ship and model; a correction to the propeller open water characteristics (ΔK_T & ΔK_Q corrections) to account for Reynolds Number dependent blade

drag scale effects; and, final empirical correction factors, obtained from each individual tow tank's data base, applied to the predicted delivered power and propeller RPM (C_P and C_N corrections). In addition, ITTC-78 uses an empirically based roughness allowance (ΔC_F) that is similar to but different than the DTMB correlation allowance, C_A. Finally, it is standard ITTC-78 procedure to not install bilge keels on ship models for either the PE or PD experiments. Rather, an estimated bilge keel drag, based on bilge keel wetted surface, is added as an adjustment to the final results.

The **differences** between the **DTMB and ITTC-78 extrapolation methods** discussed above are **summarized** :

1. ITTC-78 uses Form Factor (k) in Effective Power (PE) and Delivered Power (PD) extrapolations. DTMB does not.
2. ITTC-78 and DTMB each use a different empirically based roughness (ΔC_F) or correlation allowance (C_A).
3. ITTC-78 does not install bilge keels on ship models for either PE or PD tests. Rather, an estimated bilge keel drag, based on bilge keel wetted surface, is added as an adjustment to the final results. DTMB does install and test with bilge keels without additional correction.
4. ITTC-78 applies a correction to the model propeller open water characteristics to obtain ship scale open water characteristics to account for blade drag scale effects. DTMB does not apply this correction.
5. ITTC-78 applies a correction to the model scale wake (w_{Tm}) to obtain ship scale wake (w_{Ts}) to account for boundary layer scale effects. DTMB does not apply this correction.
6. ITTC-78 applies final corrections to predicted delivered power (C_P) and RPM (C_N) to adjust the model results to current trial statistics. DTMB does not apply this correction.

PRESENTATION AND COMPARISON OF RESULTS

Test data from the single screw Model 5326-2 were extrapolated to ship scale using both the ITTC-78 and DTMB standard ship performance prediction methods. Figure 1 is a body plan and associated coefficients for Model 5326-2.

When these model experiments were conducted, there were no plans, however, to specifically study and compare the DTMB and ITTC-78 extrapolation methods, so two of the ITTC-78 test

techniques were not strictly observed. First, bare hull model resistance experiments were not conducted. Second, bilge keels were installed on the model.

A bare hull resistance test is generally conducted in order to determine the form factor, (1+k). For this study, bare hull resistance was estimated from the appended resistance data and a bare hull form factor was then determined using the Prohaska Method. The derived value, (1+k) = 1.11, is reasonable and consistent with hullforms of this type.

Similarly, bilge keel resistance was estimated and subtracted from appended model resistance. The ITTC extrapolation was entered with this reduced resistance and then the bilge keel effects were restored, as required, in the full scale prediction of performance.

The results of the ITTC-78 and DTMB extrapolations are compared to each other in Figure 2 and Table 1. Detailed outlines and all the intermediate results of the DTMB and ITTC-78 extrapolation methods are included in Appendices A and B respectively. Both the DTMB and ITTC-78 PE and PD predictions presented here do not include still air drag or power margin.

The DTMB extrapolation method predicts higher ship effective and delivered power (PE and PD) and propeller RPM than does the ITTC-78 method. DTMB predicted PE is approximately 6% to almost 8% greater than ITTC-78 predicted PE; DTMB predicted PD is approximately 8% greater than ITTC-78 predicted PD; and, DTMB predicted RPM is approximately 1% greater than ITTC-78 predicted RPM.

The measurement uncertainty analysis shows the following overall uncertainties at the 95% confidence level: Model quantities: effective power (PE) ±1.2 % ; delivered power (PD) ±1.5 % ; RPM ±0.1 % .

DISCUSSION

Form Factor

As detailed above, the single most significant difference between the two methods is the use of form factor.

Use of form factor by ITTC-78 in the PE extrapolation results in a lower calculated coefficient of residuary resistance (C_R). This results in a lower ship scale coefficient of total resistance (C_{TS}) and therefore a lower predicted ship PE. The major difference between the ITTC-78 and DTMB PE predictions is due to the use of form factor.

Use of form factor in the PD test affects the determination of the self propulsion point. The use of the form factor results in a higher value of tow force, which, when applied to the model during the self-propulsion experiment, results in lower measured values of model thrust, torque and RPM and therefore a lower predicted ship PD and ship RPM. Corrections to the propeller open water

characteristics for blade drag scale effects and corrections to the wake are minor compared to the effect on the results due to form factor.

DTMB does not advocate the use of form factor for several reasons, both practical and theoretical. There are two practical concerns. First, form factor is very difficult to establish with any certainty. Low speed data are notoriously difficult to make use of due to significant scatter (large precision error). Thus, determining the appropriate form factor is often at best an educated guess. An example of a worst case would be a full hull form with bulb in the ballast condition. The second practical issue relates to the fact that the typical Navy ship has shafts and struts. ITTC-78 standard procedure calls for a bare hull resistance test to establish form factor. Shafts and struts are a large drag item and any form factor determined with these appendages installed would be unrealistically high. Thus for ships with shafts and struts, both a fully appended and a bare hull resistance test would always be necessary.

In addition to these practical considerations, some theoretical objections apply. Perhaps the most basic objection relates to the questionable assumption that form factor is constant across the speed range. One clear example of how form factor is not constant with speed is the case of the hullform with transom. Many Navy ships have large transoms. At slow speeds - the very speeds at which resistance data are collected to establish form factor - these transoms may have significant immersed area. The drag of the immersed transom is great due to mechanisms such as eddy-making and turbulence in the wake. As ship speed is increased, the character of the flow past the transom changes, until at some higher speed, the flow usually breaks away cleanly from the hull. Form factors established at the slower speeds do not account for this changing transom flow. These form factors tend to be unrealistically high when applied to all but the slowest ship speeds. Finally, the validity of the form factor is questionable because of the unknown extent of laminar flow on the model at these low model speeds, and the assumption that total viscous resistance is directly proportional to flat plate skin friction resistance: $C_V = (1+k)\,C_F$.

Propeller Open Water Characteristics Corrections (ΔK_T, ΔK_Q)

Correcting the model propeller open water characteristics to full scale reduces the value of the ship scale torque coefficient (K_{Qs}) with virtually no effect on the thrust coefficient (K_{Ts}). A lower K_{Qs} results in a lower predicted ship PD. This has a relatively small effect on the extrapolation results.

This is a minor correction to the propeller blade drag coefficients. It is a reasonable correction to make. However, DTMB does not apply it because of the uncertainty about what the model and full scale blade drag coefficients really are to begin with, especially with propellers operating in a

turbulent wake. The correction is within this uncertainty due to the unknown extent of laminar flow over the blade sections.

Wake Correction

This is another minor correction. It is used to adjust the model wake (w_{Tm}) to obtain ship scale wake (w_{Ts}) in order to account for boundary layer scale effects. This correction affects the prediction of full scale propeller RPM. This is also a reasonable correction to make, however DTMB does not routinely use it for the following reasons.

This is an empirical wake correction intended for single screw merchant ships, largely derived from ship / model powering tests that are, in general, conducted according to commercial practice. Many of these predictions are based on stock propeller powering tests that are adjusted for performance with design propellers. The Navy also has to deal with twin, triple and quadruple screw ships. DTMB has found that the ITTC-78 wake correction can lead to incorrect scaling trends (i.e. $w_{Ts} > w_{Tm}$) when applied to multiple screw ships.

Although DTMB will use wake scaling on a case by case basis for propeller design, depending on the magnitude of the viscous wake, the DTMB extrapolation, without this correction, works very well for Navy ships and models which tend to have the following characteristics: Navy destroyer and auxiliary hull forms which tend to be more slender than commercial ships; open shaft and strut configurations that have a relatively mild viscous wake into the propeller; Navy model tests with relatively large models at relatively high Reynolds numbers. Research to explore scaling phenomena is highly recommended.

Bilge Keels

DTMB has found that estimated bilge keel drag, based on bilge keel wetted surface, tends to under predict the actual bilge keel drag. This may be true, in part, because bilge keels on Navy ships tend to be larger than on comparable commercial ships. In addition, bilge keel drag, as a component of total drag, varies across the speed range as the flow over the bilges changes with speed and trim. A similar argument can be made for the bilge keel drag for a ship at an off design (ballast) condition. These effects are not accounted for by a simple estimate based on wetted surface.

C_A , ΔC_F , C_P And C_N Corrections

Both ΔC_F and C_A are based on formulations that are similar. The difference between ΔC_F = 0.312 E-3 (ITTC-78) and C_A = 0.300 E-3 (DTMB) has a small effect on predicted power. For

example, changing C_A from 0.300 E-3 to 0.312 E-3, increases predicted PE by approximately 0.5%.

For these calculations C_P and C_N were assumed to be equal to 1.0 and therefore had no effect on the results.

Individual tow tanks keep data bases of C_P and C_N so that their final predicted power and RPM can be individually adjusted to best predict power according to the towing facilities' experience. With the DTMB method, a single coefficient, C_A, adjusts both power and RPM simultaneously in a manner constrained by the relationship between the hull and propeller powering characteristics. The US Navy ship / model correlation data base consists of high quality data obtained at great expense. In general, the model powering tests are conducted with design propellers. Trial data are obtained during Ship Standardization Trials, which are generally conducted according to far more rigorous standards than commercial builder's trials.

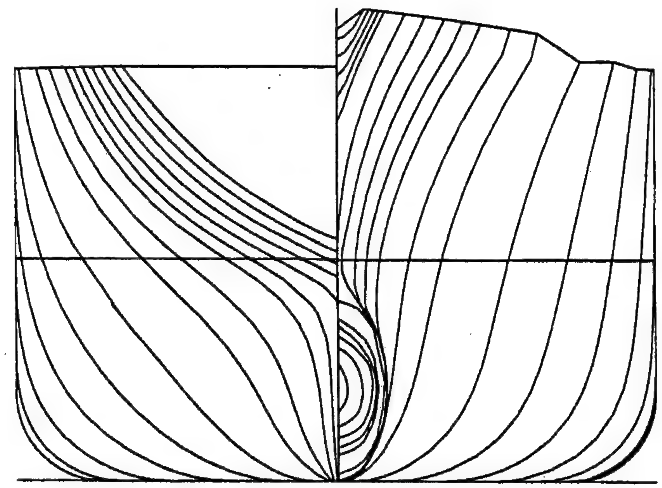
In General

Virtually every towing tank that claims to adhere to ITTC-78 practice, customizes some details of the method. This customization is often a reasonable and necessary variation. Often, the variation takes the form of a simplification, as in eliminating the wake scaling for a twin screw ship. One advantage of the DTMB method is its simplicity. Predicted ship delivered power can be derived from a correlation allowance, provided from the Navy historical database, and the measured model quantities: propeller torque, propeller RPM, model speed and Tow force F_D. Though information from the resistance and propeller open water tests is routinely used for the calculation of the hull-propeller interaction factors, the ship delivered power can be predicted based on the powering test data alone. On the other hand, the ITTC-78 method requires these model self propulsion test measurements plus input from a bare hull resistance test to determine (1+k), open water tests, estimates of ship hull roughness and ship propeller roughness, and often the final corrections, C_P and C_N.

CONCLUSION

In the case of this comparison, the DTMB extrapolation method predicts higher ship effective and delivered power (PE and PD) and propeller RPM than does the ITTC-78 method. DTMB predicted PE is approximately 6% to almost 8% greater than ITTC-78 predicted PE; DTMB predicted PD is approximately 8% greater than ITTC-78 predicted PD; and, DTMB predicted RPM is approximately 1% greater than ITTC-78 predicted RPM. The principal reason for the difference between these two predictions is that the ITTC-78 method uses the form factor approach and the DTMB method does not.

MODEL 5326-2



PRINCIPAL DIMENSIONS

LENGTH (LBP)	=	658.00 ft	(200.56 m)
LENGTH (LWL)	=	660.61 ft	(201.35 m)
BEAM (B_X)	=	88.00 ft	(26.82 m)
DRAFT (T_X)	=	30.60 ft	(9.35 m)
TRIM (+Bow)	=	-0.20 ft	(-0.06 m)
DISPLACEMENT	=	33584.0 T	(34121. t)
WETTED SURFACE	=	72829 sqft	(6765.9 sqm)

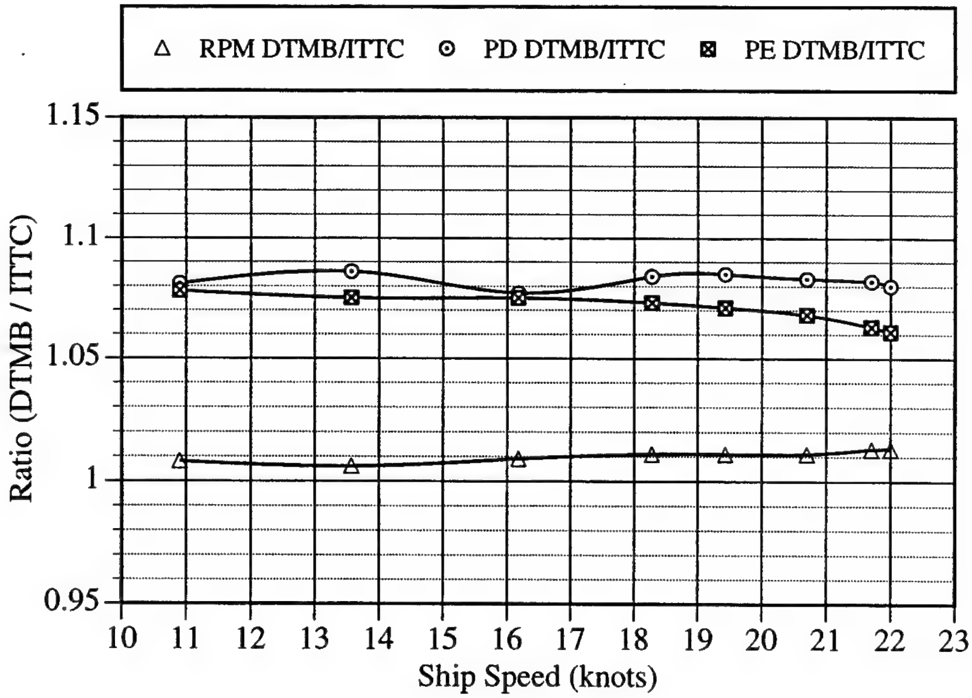
NONDIMENSIONAL COEFFICIENTS

C_B	= 0.659	C_{VP}	= 0.869	L_E/LWL	= 0.578
C_P	= 0.673	C_{VPF}	= 0.917	L_P/LWL	= 0.000
C_{PF}	= 0.662	C_{VPA}	= 0.828	L_R/LWL	= 0.422
C_{PA}	= 0.686	C_S	= 2.614	FB/LWL	= 0.505
C_{PE}	= 0.707	LWL/B_X	= 7.507	FF/LWL	= 0.525
C_{PR}	= 0.627	B_X/T_X	= 2.869	$100C_\nabla$	= 0.407
C_X	= 0.979	A_T/A_X	= 0.000	S	= 6.542
C_{WP}	= 0.758	B_T/B_X	= 0.000	M	= 6.237
C_{WPF}	= 0.707	T_T/T_X	= 0.000	$\Delta/(.01LWL)^3$	= 116.5
C_{WPA}	= 0.808	A_B/A_X	= 0.090		

MODEL SCALE DATA

SCALE RATIO	=	25.682	
LENGTH (LBP)	=	25.62 ft	(7.81 m)
LENGTH (LWL)	=	25.72 ft	(7.84 m)
BEAM (B_X)	=	3.43 ft	(1.04 m)
DRAFT (T_X)	=	1.19 ft	(0.36 m)
DISPLACEMENT	=	4318.5 lbs	(1.96 t)
WETTED SURFACE	=	110.42 sqft	(10.26 sqm)

Fig. 1. Body plan and associated coefficients for Model 5326-2.



Ship Speed (knots)	Ratio (DTMB / ITTC-78)		
	RPM	PD	PE
10.90	1.008	1.081	1.079
13.57	1.006	1.086	1.076
16.18	1.009	1.077	1.075
18.28	1.011	1.084	1.073
19.43	1.011	1.085	1.071
20.70	1.011	1.083	1.068
21.70	1.013	1.082	1.063
22.00	1.013	1.080	1.061

Fig. 2. Comparison of ITTC-78 to DTMB Standard Performance Prediction Results

Table 1. Comparison of ITTC-78 and DTMB intermediate extrapolation results - Data spot for 22 knot ship speed (Fn = 0.255).

Extrapolation Results for Model Speed = 4.34 knots, Ship Speed = 22 knots (Fn = 0.255), λ = 25.682		
	ITTC-78	DTMB
PE Test:		
R_{Tm} (lbf)	20.67 (no B.K.)	21.22 (w/B.K.)
C_{Tm}	3.510	3.497
C_{Fm}	2.737	2.737
1+k	1.110	---
$(1+k)*C_{Fm}$	3.038	---
$C_{Rm}=C_{Rs}$	0.472	0.760
C_{Fs}	1.367	1.367
$(1+k)*C_{Fs}$	1.518	---
ΔC_F or C_A	0.312 (ΔC_F)	0.300 (C_A)
$(S_S+S_{BK})/S_S$	1.031	---
C_{Ts}	2.358	2.427
PE (Hp) (w/ B.K.)	16264	17257
PD Test:		
Model Scale Quantities:		
Tow Force (lbf)	7.33 (R_A)	6.49 (F_D)
T_m (lbf)	16.33	17.26
Q_m (lbf-in)	32.33	33.91
n_m (1/s)	8.41	8.53
K_{Tm}	0.266	0.274
K_{Qm}	0.054	0.055
J_A	1.065	1.050
$1-w_{Tm}$	0.799	0.797
η_R	0.984	0.982
1-t	0.850	0.853
Ship Scale Quantities:		
$1-w_{Ts}$	0.803	no correction
K_{Ts}	0.266	"
K_{Qs}	0.052	"
T_s (klbf)	283.4	299.7
Q_s (klbf-ft)	1181.5	1259.8
n_s (RPM)	99.7	101.0
PD (Hp) (w/ B.K.)	22438	24237
η_D	0.725	0.712

Note: ITTC-78 does not install bilge keels on ship models for either PE or PD tests. Rather, an estimated bilge keel drag, based on bilge keel wetted surface, is added as an adjustment to the final Full Scale results. DTMB does install and test with bilge keels without additional correction. The ITTC and DTMB predictions of ship PE and PD shown here both include the effects of bilge keels.

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APPENDIX A

DTMB STANDARD SHIP PERFORMANCE PREDICTION METHOD OUTLINE AND RESULTS

APPENDIX A

DTMB STANDARD SHIP PERFORMANCE PREDICTION METHOD OUTLINE AND RESULTS

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OUTLINE OF THE STANDARD DTMB MODEL RESISTANCE AND SELF-PROPULSION TEST AND SHIP PERFORMANCE EXTRAPOLATION METHODS A3

Table A1. DTMB predicted effective power results A6

Table A2. DTMB predicted powering performance results.. A7

Figure A1. Open water characteristics of Model Propeller 5027A..................................... A8

OUTLINE OF THE STANDARD DTMB MODEL RESISTANCE AND SELF-PROPULSION TEST AND SHIP PERFORMANCE EXTRAPOLATION METHODS

RESISTANCE (PE) TEST

1. Tow model at speed corresponding to equal ship scale Froude Number. Measure model Total Resistance ,R_{Tm} (lbf).

2. Calculate model Total Resistance Coefficient:

$$C_{Tm} = R_{Tm} / (1/2\, \rho_m S_m V_m^2)$$

3. Calculate model and ship Frictional Resistance Coefficients:

$$C_{Fm,s} = 0.075 \;/\; (\log_{10} R_n - 2)^2 \quad \text{(ITTC 1957 ship-model correlation line)}$$

4. Solve for Residuary Resistance Coefficient:

$$C_R = C_{Rm} = C_{Rs} = C_{Tm} - C_{Fm}$$

5. Calculate ship Total Resistance Coefficient:

$$C_{Ts} = C_R + C_{Fs} + C_A \quad (C_A \text{ from Navy ship/model correlation data base})$$

6. Calculate ship effective power:

$$PE = C_{Ts} (1/2\, \rho_s S_s V_s^3) / 550 \quad \text{(Hp)}$$

SELF-PROPULSION (PD) TEST

1. Tow model at speed corresponding to equal ship scale Froude Number. Adjust model propeller revolution rate so that there is a tow force, F_D, applied to the model equal to:

$$F_D = 1/2\, \rho_m S_m V_m^2 [C_{Fm} - (C_{Fs} + C_A)]$$

2. Measure model propeller thrust, T_m (lbf), torque, Q_m (in-lbf), and rate of revolution ,n_m (1/s).

3. Express T_m and Q_m in nondimensional coefficient form:

$$K_{Tm} = T_m \;/\; (\rho_m D_m^4 n_m^2) \quad \text{and} \quad K_{Qm} = Q_m \;/\; (\rho_m D_m^5 n_m^2)$$

4. With K_{Tm} as the input, determine the advance ratio, J_{Tm} (@K_{Tm}), and the torque coefficient, K_{QTm} (@K_{Tm}), from the model propeller open water characteristics curves.

5. The following Ship Scale quantities are calculated:

Propeller rate (1/min):	$n_s = (n_m \cdot 60) / \lambda^{0.5}$	
Delivered Power (Hp)	$PD = \dfrac{(Q_m \lambda^4)(n_s) 2\pi\rho_s}{12 \cdot 33000 \cdot \rho_m}$	
Thrust deduction factor	$1\text{-}t = (R_{Tm} - F_D) / T_m$	with R_{Tm} from resistance test
Thrust Wake factor	$1\text{-}w_T = J_{Tm} / J_A$	where $J_A = V_m /(n_m \cdot D_m)$
Hull efficiency	$\eta_h = 1\text{-}t / 1\text{-}w_T$	
Relative Rotative Efficiency	$\eta_R = K_{QTm} / K_{Qm}$	
Propulsive efficiency	$\eta_D = PE / PD$	with PE from resistance test

where

m		used as a subscript denotes model scale
s		used as a subscript denotes ship scale
C_A	=	Ship/Model Correlation Allowance (from Navy Correlation Database)
C_F	=	Frictional Resistance Coefficient (ITTC-78 Friction Line)
C_R	=	Residuary Resistance Coefficient
C_T	=	Total Resistance Coefficient
D	=	Propeller diameter (ft)
F_D	=	Towing Force- friction correction - in self propulsion test
η_H	=	Hull efficiency
η_R	=	Relative rotative efficiency
J	=	Propeller advance ratio $= V_A / (n\, D)$
J_A	=	Apparent or hull advance ratio $= V / (n\, D)$
J_T	=	Propeller advance ratio based on thrust identity (@ K_T)

K_Q	=	Propeller Torque Coefficient
K_{QT}	=	Propeller Torque Coefficient based on thrust identity (@ K_T)
K_T	=	Propeller Thrust Coefficient
λ	=	linear scale ratio
n	=	Propeller rate of revolution (1/s)
PD	=	Delivered Power at Propeller (Horsepower)
PE	=	Effective Power (Horsepower)
Q	=	Torque (in-lbf, model ; ft-lbf, ship)
R_n	=	Reynolds Number
R_T	=	Total resistance (lbf)
ρ	=	Mass density of water (lbf $\cdot$ s^2/ft^4)
S	=	Wetted surface (ft^2)
t	=	Thrust Deduction Fraction
T	=	Thrust (lbf)
V	=	Speed ,velocity (ft/s)
w_T	=	Wake Fraction (thrust identity)

550	550 ft-lbf/(s· Horsepower)
12; 33000	12 inches / ft ; 33000 ft-lbf / (minute · Horsepower)

Table A 1. DTMB predicted effective power results

	SHIP	MODEL	
λ		25.682	
L_{WL}	660.61	25.723	ft
S	76971.00	116.700	ft^2
Δ	33584.00	4318.50	LT ; lbf
ρ	1.9847	1.9369	lbf*s^2/ft^4
ν	9.6170E-06	1.0983E-05	ft^2/s
C_A		0.00030	

No Still Air Drag, No Power Margin

Vs knots	Vm ft/s	RTm lbf	CTm	CFm	CR
10.90	3.63	5.30	3.561E-03	3.086E-03	4.750E-04
13.57	4.52	7.94	3.440E-03	2.971E-03	4.690E-04
16.18	5.39	10.88	3.314E-03	2.882E-03	4.320E-04
18.28	6.09	13.66	3.261E-03	2.823E-03	4.380E-04
19.43	6.47	15.45	3.264E-03	2.795E-03	4.690E-04
20.70	6.89	17.77	3.309E-03	2.765E-03	5.440E-04
21.70	7.23	20.22	3.425E-03	2.743E-03	6.820E-04
22.00	7.33	21.22	3.497E-03	2.737E-03	7.600E-04

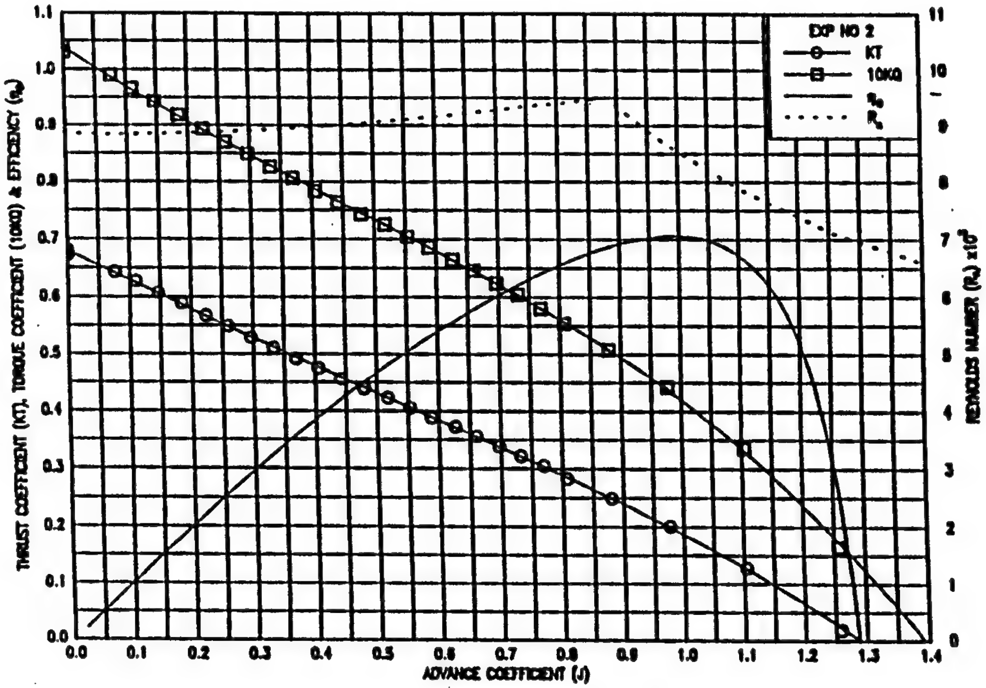
Vs knots	Vs ft/s	CFs	CTs	RTs lbf	PEs Hp
10.90	18.397	1.487E-03	2.262E-03	58479	1956
13.57	22.903	1.448E-03	2.217E-03	88832	3699
16.18	27.309	1.418E-03	2.150E-03	122458	6080
18.28	30.853	1.397E-03	2.135E-03	155258	8709
19.43	32.794	1.387E-03	2.156E-03	177128	10561
20.70	34.937	1.377E-03	2.221E-03	207070	13154
21.70	36.625	1.369E-03	2.351E-03	240920	16043
22.00	37.132	1.367E-03	2.427E-03	255609	17257

Table A2. DTMB predicted powering performance results.

SHIP LENGTH	660.6 FEET	(201.4 METERS)	
SHIP DISPLACEMENT	33584. TONS	(34123. METRIC TONS)	
SHIP WETTED SURFACE	76971. SQFT	(7151. SQ METERS)	
CORRELATION ALLOWANCE	.00030	ITTC FRICTION USED	
NO STILL AIR DRAG, NO POWER MARGIN			

SHIP SPEED (KTS)	SHIP SPEED (M/S)	RESIDUARY RES.COEF. (CR*1000)	EFFECTIVE POWER- PE (HP)	EFFECTIVE POWER- PE (kW)	DELIVERED POWER- PD (HP)	DELIVERED POWER- PD (kW)	PROPELLER REV. PER MINUTE
10.9	5.61	0.475	1956.1	1458.6	2608.1	1944.9	48.2
13.6	6.98	0.469	3699.2	2758.5	4985.4	3717.6	59.8
16.2	8.32	0.432	6080.3	4534.0	8128.7	6061.6	70.7
18.3	9.40	0.438	8709.4	6494.6	11769.5	8776.5	80.1
19.4	10.00	0.469	10561.3	7875.6	14447.8	10773.7	85.5
20.7	10.65	0.544	13153.6	9808.7	18168.0	13547.9	92.0
21.7	11.16	0.682	16043.2	11963.4	22438.0	16732.0	98.6
22.0	11.32	0.760	17256.7	12868.3	24236.9	18073.5	101.0

SHIP SPEED (KTS)	EFFICIENCIES (ETA) ETAD	ETAO	ETAH	ETAR	ETAB	THRUST DEDUCTION AND WAKE FACTORS 1-THDF	1-WFTT	1-WFTQ	ADVANCE COEF. ADVC
10.9	0.750	0.680	1.125	0.980	0.665	0.870	0.775	0.760	0.845
13.6	0.740	0.680	1.115	0.975	0.665	0.865	0.775	0.755	0.845
16.2	0.750	0.685	1.120	0.975	0.670	0.870	0.780	0.760	0.860
18.3	0.740	0.685	1.100	0.980	0.670	0.860	0.780	0.765	0.860
19.4	0.730	0.685	1.090	0.980	0.670	0.850	0.775	0.760	0.850
20.7	0.725	0.680	1.085	0.980	0.665	0.845	0.775	0.765	0.845
21.7	0.715	0.680	1.075	0.980	0.665	0.850	0.790	0.780	0.840
22.0	0.710	0.675	1.070	0.980	0.665	0.855	0.795	0.785	0.835



J	K_T	$10K_Q$	η_o
0.000	0.687	1.044	0.000
0.050	0.656	1.005	0.052
0.100	0.627	0.968	0.103
0.150	0.600	0.934	0.153
0.200	0.573	0.902	0.202
0.250	0.548	0.872	0.250
0.300	0.524	0.844	0.297
0.350	0.500	0.816	0.342
0.400	0.477	0.789	0.385
0.450	0.455	0.763	0.427
0.500	0.432	0.736	0.467
0.550	0.410	0.709	0.506
0.600	0.387	0.682	0.542
0.650	0.364	0.654	0.576
0.700	0.341	0.625	0.608
0.750	0.317	0.595	0.636
0.800	0.292	0.563	0.662
0.850	0.267	0.529	0.683
0.900	0.241	0.493	0.698
0.950	0.213	0.455	0.707
1.000	0.184	0.415	0.707
1.050	0.154	0.372	0.693
1.100	0.123	0.327	0.660
1.150	0.090	0.278	0.594
1.200	0.056	0.226	0.470
1.250	0.019	0.171	0.226

MODEL PROPELLER CHARACTERISTICS

DIAMETER 9.812 inches (249.225 mm) CHORD LENGTH (0.7R) 3.827 inches (97.206 mm)

P/D (0.7R) 1.228 5 BLADES RH ROTATION

Fig. A1. Open water characteristics of Model Propeller 5027A.

APPENDIX B

ITTC-78 SHIP PERFORMANCE PREDICTION METHOD OUTLINE AND RESULTS

APPENDIX B

ITTC-78 SHIP PERFORMANCE PREDICTION METHOD OUTLINE AND RESULTS

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OUTLINE OF THE ITTC-78 MODEL RESISTANCE AND SELF-PROPULSION TEST AND SHIP PERFORMANCE EXTRAPOLATION METHODS B3

Figure B1. Prohaska plot for determining Form Factor (1+k) B7

Table B1. ITTC-78 predicted effective power results B8

Table B2. ITTC-78 predicted powering performance results B9

OUTLINE OF THE ITTC-78 PROPELLER OPEN WATER TEST METHOD AND CORRECTION B11

Figure B2. Model Propeller 5027A Open Water Characteristics and ITTC-78 Corrected Ship Scale Values B13

Table B3. Model Propeller 5027A Open Water Characteristics and ITTC-78 Corrected Ship Scale Values B14

OUTLINE OF THE ITTC-78 MODEL RESISTANCE AND SELF-PROPULSION TEST AND SHIP PERFORMANCE EXTRAPOLATION METHODS

RESISTANCE (PE) TEST

1. Conduct bare hull resistance test. Determine form factor (1+k) using Prohaska Method.

2. Tow model at speed corresponding to equal ship scale Froude Number. Measure model Total Resistance, R_{Tm}. Note that model does not have bilge keels fitted to it during either the resistance (PE) or self-propulsion (PD) experiments.

3. Calculate model Total Resistance Coefficient:

$$C_{Tm} = R_{Tm} / (1/2\, \rho_m S_m V_m^2)$$

4. Calculate model and ship Frictional Resistance Coefficients:

$$C_{Fm,s} = 0.075 \ / \ (\log_{10} R_n - 2)^2 \quad \text{(ITTC 1957 ship-model correlation line)}$$

5. Solve for Residuary Resistance Coefficient:

$$C_R = C_{Rm} = C_{Rs} = C_{Tm} - (1+k)\, C_{Fm}$$

6. Calculate ship Total Resistance Coefficient:

$$C_{Ts} = [(S_S + S_{BK}) / S_S]\, [(1+k)\, C_{Fs} + \Delta C_F] + C_R$$

7. Calculate ship effective power:

$$PE = C_{Ts}\, (1/2\, \rho_s S_s V_s^3) \cdot 10^{-6} \quad \text{(megawatts)}$$

SELF-PROPULSION (PD) TEST

1. Tow model at speed corresponding to equal full scale Froude Number. Adjust model propeller revolution rate so that there is a tow force, R_A, applied to the model equal to:

$$R_A = 1/2\, \rho_m S_m V_m^2 [\, 1+k \cdot C_{Fm} - (1+k \cdot C_{Fs} + \Delta C_F\,)]$$

2. Measure model propeller thrust (T), torque (Q) and rate of revolution (n). Express T and Q in nondimensional coefficient form:

$$K_{Tm} = T \,/\, (\rho\, D^4\, n^2)_m \quad \text{and} \quad K_{Qm} = Q \,/\, (\rho\, D^5\, n^2)_m$$

3. With K_{Tm} as the input, determine the advance ratio, J_{Tm} (@K_{Tm}), and the torque coefficient, K_{QTm} (@K_{Tm}), from the propeller open water characteristics curves.

4. Calculate the model scale wake fraction, w_{Tm} :

$$w_{Tm} = 1 - [(J_{Tm} \cdot D_m \cdot n) / V_m]$$

5. Calculate relative rotative efficiency, η_R, and thrust deduction fraction, t :

$$\eta_R = K_{QTm} / K_{Qm} \quad \text{and} \quad t = (T + R_A - R_{Tm}) / T$$

where

$\eta_R = \eta_{Rs} = \eta_{Rm}$, $t = t_s = t_m$ and R_{Tm} = measured model total resistance from the resistance test, corrected for the difference in water temperature between the resistance and self-propulsion test.

6. Calculate the full scale wake, w_{Ts}, by correcting the model scale wake, w_{Tm} :

$$w_{Ts} = (t + 0.04) + (w_{Tm} - t - 0.04)\frac{(1+k)C_{Fs} + \Delta C_F}{(1+k)C_{Fm}}$$

7. Thrust loading on the full scale propeller is determined:

$$\frac{K_{Ts}}{J^2} = \frac{S_S}{2D_s^{\,2}} \cdot \frac{C_{Ts}}{(1-t)(1-w_{Ts})^2}$$

where

C_{Ts} = ship total resistance coefficient , determined in resistance experiment.

8. With K_{Ts} / J^2 as the input, determine the advance ratio, J_{Ts}, and the torque coefficient, K_{QTs}, from the full scale propeller open water characteristics curves. (Note that the model scale propeller open water characteristics have been corrected for blade drag scale effects to give the full scale propeller open water characteristics. See the following section of this appendix.)

9. The following ship scale quantities are calculated:

Propeller rate of revolution (1/s):	$n_s = [(1-w_{Ts}) \cdot V_s] / (J_{Ts} \cdot D_s)$
Delivered Power (megawatts)	$PD = 2\pi \rho_s D^5 n_s^3 (K_{QTs} / \eta_R) \cdot 10^{-6}$
Propeller thrust (kN)	$T_s = (K_{Ts} / J^2) \cdot J_{Ts}^2 \rho_s D^4 n_s^2 10^{-3}$
Propeller torque (kNm)	$Q_s = (K_{QTs} / \eta_R) \cdot \rho_s D^5 n_s^2 10^{-3}$
Propulsive efficiency	$\eta_D = PE / PD$ with PE from resistance test

10. Final correction factors (C_P, C_N) are applied to the predicted delivered power (PD) and shaft revolution rate (n_s) to correct the prediction for specific Trial conditions (PD_T and n_T).

$$n_T = C_N \cdot n_s \ , \quad PD_T = C_P \cdot PD$$

where

m		used as a subscript denotes model scale
s		used as a subscript denotes ship scale
C_F	=	Frictional Resistance Coefficient (ITTC-78 Friction Line)
ΔC_F	=	Roughness allowance formula (empirical) $= [105 \cdot (k_s / L)^{1/3} - 0.64] \cdot 10^{-3}$
C_N	=	Trial correction for propeller rate of revolution at speed identity
C_P	=	Trial correction for delivered power
C_R	=	Residuary Resistance Coefficient
C_T	=	Total Resistance Coefficient
D	=	Propeller diameter (m)
η_R	=	Relative rotative efficiency
J	=	Propeller advance ratio $= V_A / (n\,D)$
J_T	=	Propeller advance ratio based on thrust identity (@ K_T)
k	=	Form factor determined in resistance test
k_s	=	Hull roughness ($150 \cdot 10^{-6}$ m recommended)
K_Q	=	Propeller Torque Coefficient
K_{QT}	=	Propeller Torque Coefficient based on thrust identity (@ K_T)
K_T	=	Propeller Thrust Coefficient
L	=	Length (m)
n	=	Propeller rate of revolution (1/s)
n_T	=	Propeller rate of revolution - ship scale corrected to specific trial conditions (1/s)
PD	=	Delivered Power at Propeller (megawatts)

PD_T	=	Delivered Power at Propeller corrected to specific trial conditions (megawatts)
PE	=	Effective Power (megawatts)
Q	=	Torque (N m)
R_A	=	Tow Force (N)
R_n	=	Reynolds Number
R_T	=	Total resistance (N)
ρ	=	Mass density of water (kg/m^3)
S	=	Wetted surface (m^2)
S_{BK}	=	Wetted surface of bilge keels - ship scale (m^2)
t	=	Thrust Deduction Fraction
T	=	Thrust (N)
V	=	Speed ,velocity (m/s)
V_A	=	Propeller advance speed (m/s)
w_T	=	Wake Fraction (thrust identity)

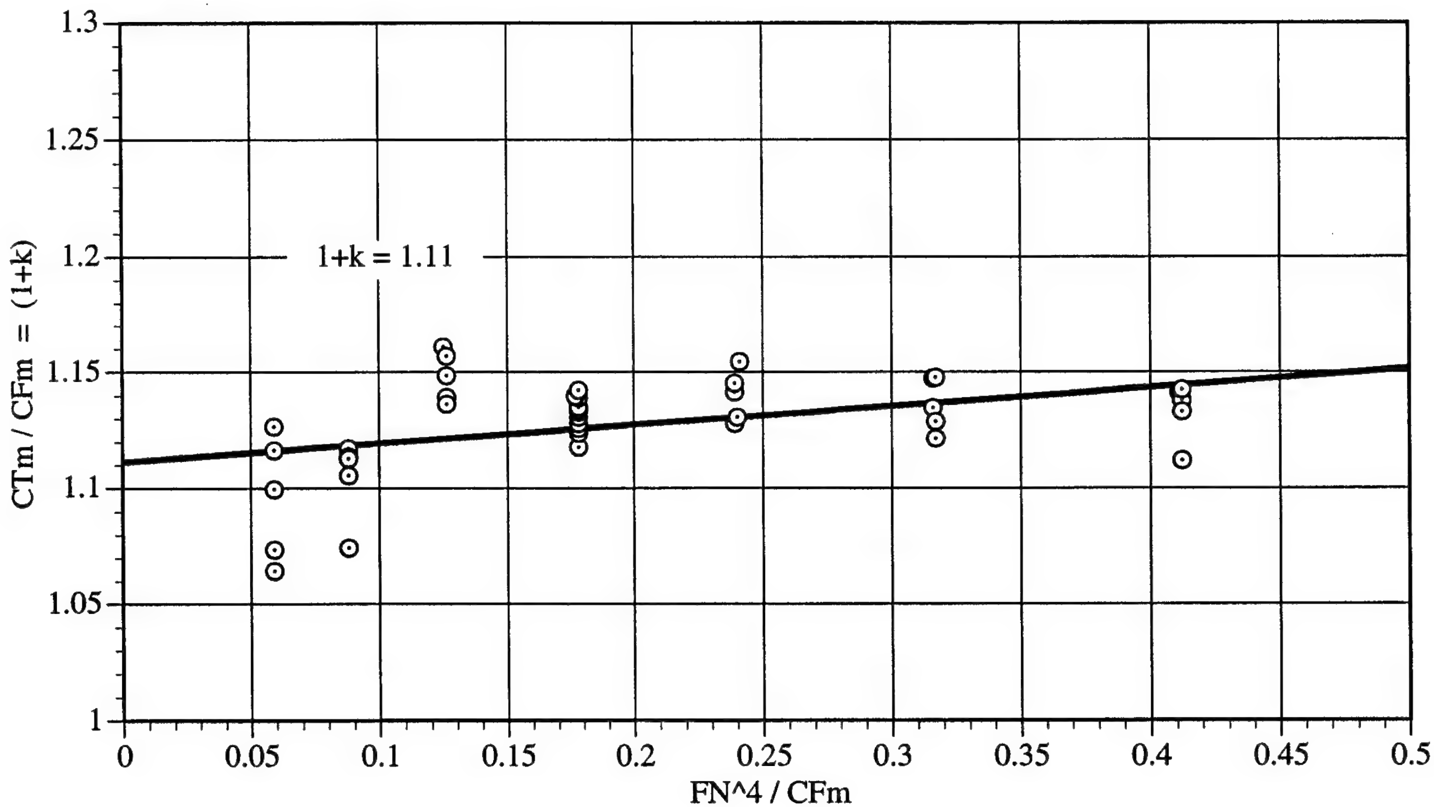

Fig. B1. Prohaska plot for determining Form Factor (1+k).

Table B1. ITTC-78 predicted effective power results.

	U.S. Customary SHIP	MODEL		Metric SHIP	MODEL	
λ		25.682			25.682	
L_{WL}	660.61	25.72	ft	201.35	7.840	m
S	74682.00	113.23	ft^2	6938.18	10.519	m^2
Sbk	2289.00		ft^2	212.65		m^2
Δ	33584.00	4318.50	LT; lbf	33262.75	1.915	m^3
ρ	1.9847	1.9369	lbf*s^2/ft^4	1022.87	998.237	Kg/m^3
ν	.9617E-05	1.0983E-05	ft^2/s	.8934E-06	1.0204E-06	m^2/s
ΔC_F		.3118E-03			.3118E-03	
1+k		1.11			1.11	

No Still Air Drag, No Power Margin

V_s kts	V_m m/s	R_{Tm} N	R_{Tm} lbf	C_{Fm}	$(1+k)*C_{Fm}$	C_{Tm}	$C_{Rm}=C_{Rs}$
10.90	1.11	22.91	5.15	3.086E-03	3.426E-03	3.565E-03	1.387E-04
13.57	1.38	34.30	7.71	2.971E-03	3.297E-03	3.443E-03	1.456E-04
16.18	1.64	46.98	10.56	2.882E-03	3.199E-03	3.317E-03	1.176E-04
18.28	1.86	59.02	13.27	2.823E-03	3.134E-03	3.264E-03	1.304E-04
19.43	1.97	66.74	15.00	2.795E-03	3.102E-03	3.268E-03	1.657E-04
20.70	2.10	76.87	17.28	2.765E-03	3.069E-03	3.316E-03	2.463E-04
21.70	2.20	87.55	19.68	2.743E-03	3.045E-03	3.436E-03	3.910E-04
22.00	2.23	91.93	20.67	2.737E-03	3.038E-03	3.510E-03	4.721E-04

V_s kts	V_s m/s	C_{Fs}	$(1+k)*C_{Fs}$	ΔCF	C_{Ts}	PE MW	PE Hp
10.90	5.607	1.487E-03	1.651E-03	3.118E-04	2.161E-03	1.352	1813
13.57	6.981	1.448E-03	1.607E-03	3.118E-04	2.124E-03	2.564	3438
16.18	8.324	1.418E-03	1.574E-03	3.118E-04	2.061E-03	4.217	5656
18.28	9.404	1.397E-03	1.551E-03	3.118E-04	2.050E-03	6.051	8114
19.43	9.996	1.387E-03	1.540E-03	3.118E-04	2.074E-03	7.350	9857
20.70	10.649	1.377E-03	1.528E-03	3.118E-04	2.143E-03	9.183	12314
21.70	11.163	1.369E-03	1.520E-03	3.118E-04	2.279E-03	11.250	15087
22.00	11.318	1.367E-03	1.518E-03	3.118E-04	2.358E-03	12.128	16264

Table B2. ITTC-78 predicted powering performance results.

	U.S. Customary SHIP	U.S. Customary MODEL		Metric SHIP	Metric MODEL	
λ		25.682			25.682	
L_{WL}	660.61	25.72	ft	201.35	7.840	m
S	74682.00	113.23	ft^2	6938.18	10.519	m^2
Sbk	2289.00		ft^2	212.65		m^2
Δ	33584.00	4318.50	LT; lbf	33262.75	1.915	m^3
D	21.00	9.812	ft ; in	6.40	0.249	m
ρ	1.9847	1.9369	lbf*s^2/ft^4	1022.87	998.237	Kg/m^3
ν	.9617E-05	1.0983E-05	ft^2/s	.8934E-06	1.0204E-06	m^2/s
ΔC_F		.3118E-03			.3118E-03	
1+k		1.11			1.11	

No Still Air Drag, No Power Margin

Measured Model Tow Force (R_A), Thrust (T_m), Torque (Q_m) and Propeller Rotation Rate (N_m) at the ITTC-78 defined self-propulsion point :

V_s kts	V_m m/s	R_A N	T_m N	Q_m N-m	N_m 1/s
10.90	1.106	9.695	15.974	0.814	3.981
13.57	1.378	14.152	24.520	1.249	4.969
16.18	1.642	19.179	33.874	1.740	5.845
18.28	1.856	23.683	43.638	2.219	6.649
19.43	1.972	26.318	50.195	2.552	7.103
20.70	2.101	29.364	59.008	2.989	7.662
21.70	2.203	31.862	68.451	3.456	8.215
22.00	2.233	32.628	72.640	3.653	8.415

Model scale quantities (uncorrected) :

V_s kts	V_m m/s	K_{Tm}	K_{Qm}	J_A	J_{Tm} @K_{Tm}	K_{QTm} @K_{Tm}
10.90	1.106	0.26162	0.05346	1.11507	0.85946	0.05223
13.57	1.378	0.25781	0.05270	1.11228	0.86673	0.05172
16.18	1.642	0.25745	0.05306	1.12755	0.86742	0.05167
18.28	1.856	0.25630	0.05229	1.11986	0.86960	0.05152
19.43	1.972	0.25827	0.05269	1.11411	0.86585	0.05178
20.70	2.101	0.26095	0.05303	1.10036	0.86075	0.05214
21.70	2.203	0.26336	0.05335	1.07593	0.85614	0.05246
22.00	2.233	0.26635	0.05374	1.06489	0.85039	0.05286

V_s kts	V_m m/s	w_{Tm}	$1-w_{Tm}$	η_R	t	1-t
10.90	1.106	0.229	0.771	0.977	0.130	0.870
13.57	1.378	0.221	0.779	0.981	0.137	0.863
16.18	1.642	0.231	0.769	0.974	0.138	0.862
18.28	1.856	0.223	0.777	0.985	0.150	0.850
19.43	1.972	0.223	0.777	0.983	0.156	0.844
20.70	2.101	0.218	0.782	0.983	0.158	0.842
21.70	2.203	0.204	0.796	0.983	0.151	0.849
22.00	2.233	0.201	0.799	0.984	0.150	0.850

Table B2. ITTC-78 predicted powering performance results (Continued).

Ship scale quantities (corrected) :

V_s kts	w_{Ts}	$1-w_{Ts}$	J_{Ts}	K_{Ts}	K_{QTs}
10.90	0.204	0.796	0.87555	0.25450	0.05038
13.57	0.202	0.798	0.87864	0.25287	0.05016
16.18	0.209	0.791	0.88136	0.25142	0.04996
18.28	0.210	0.790	0.87871	0.25282	0.05015
19.43	0.212	0.788	0.87349	0.25558	0.05052
20.70	0.210	0.790	0.86664	0.25918	0.05101
21.70	0.199	0.801	0.86027	0.26252	0.05146
22.00	0.197	0.803	0.85423	0.26567	0.05188

V_s kts	N_s 1/s	PD MW	T_s kN	Q_s kNm	η_D
10.90	0.797	1.80	277.2	359.6	0.752
13.57	0.990	3.42	425.5	550.5	0.749
16.18	1.167	5.63	587.9	767.8	0.749
18.28	1.321	8.10	757.3	976.0	0.747
19.43	1.409	9.93	871.1	1121.6	0.741
20.70	1.517	12.51	1024.0	1312.0	0.735
21.70	1.623	15.46	1187.9	1515.7	0.728
22.00	1.662	16.73	1260.6	1601.8	0.725

V_s kts	N_s RPM	PD Hp	T_s lbf	Q_s ft-lbf	η_D
10.90	47.8	2413	62325	265194	0.752
13.57	59.4	4593	95666	406062	0.749
16.18	70.0	7550	132162	566310	0.749
18.28	79.3	10862	170250	719845	0.747
19.43	84.5	13316	195830	827284	0.741
20.70	91.0	16770	230212	967669	0.735
21.70	97.4	20733	267056	1117899	0.728
22.00	99.7	22438	283395	1181460	0.725

OUTLINE OF THE ITTC-78 PROPELLER OPEN WATER TEST METHOD AND CORRECTION

1. The model propeller is attached to a horizontal shaft and advanced, propeller first, into undisturbed water. The shaft center is located at a depth of at least one propeller diameter below the free surface.

2. Propeller thrust (T), torque (Q) and rate of revolution (n) are measured throughout the loading range of the propeller which is covered by various combinations of propeller rate of revolution, n, and speed of advance (V_A).

3. Express T and Q in nondimensional coefficient form:

$$K_{Tm} = T \,/\, (\rho D^4 n^2)_m \quad \text{and} \quad K_{Qm} = Q \,/\, (\rho D^5 n^2)_m$$

4. Propeller open water efficiency and advance ratio are calculated:

$$\eta_O = (J K_{Tm}) / (2 \pi K_{Qm}) \;, \quad J = V_A / (n D)$$

5. All the coefficients and quantities shown in steps 1 through 4 above refer to the model propeller. These model scale quantities are now corrected for blade drag scale effects to get ship scale values for the Propeller Thrust Coefficient and Propeller Torque Coefficient.

$$K_{Ts} = K_{Tm} - \Delta K_T \quad \text{and} \quad K_{Qs} = K_{Qm} - \Delta K_Q$$

where

$$\Delta K_T = -\,\Delta C_D \cdot 0.3 \cdot (P/D) \cdot (cZ/D) \quad \text{and} \quad \Delta K_Q = \Delta C_D \cdot 0.25 \cdot (cZ/D)$$

The difference in the blade drag coefficient is:

$$\Delta C_D = C_{Dm} - C_{Ds}$$

$$C_{Dm} = 2\left(1+2\frac{tb}{c}\right)\left[\frac{0.044}{(R_{nco})^{1/6}} - \frac{5}{(R_{nco})^{2/3}}\right] \quad \text{and} \quad C_{Ds} = 2\left(1+2\frac{tb}{c}\right)\left[1.89+1.62\cdot\log\frac{c}{k_p}\right]^{-2.5}$$

The propeller blade Reynolds number at the 0.75 r/R is:

$$R_{nco} = (c\,V)/\nu \qquad \text{where} \qquad V = V_A\sqrt{1+\left(\frac{\pi\cdot 0.75}{J}\right)^2}$$

Where,

m		used as a subscript denotes model scale
s		used as a subscript denotes ship scale
c	=	Propeller blade chord length at 0.75 r /R
C_D	=	Propeller blade drag coefficient
D	=	Propeller diameter (m)
ηo	=	Propeller efficiency in open water
J	=	Propeller advance ratio
k_p	=	Propeller blade roughness - ship scale ($30 \cdot 10^{-6}$ m recommended)
K_Q	=	Propeller Torque Coefficient
K_T	=	Propeller Thrust Coefficient
n	=	Propeller rate of revolution (1/s)
ν	=	kinematic viscosity (m^2/s)
P	=	Propeller blade pitch at 0.75 r/R (m)
Q	=	Torque (N m)
R_{nco}	=	Propeller blade Reynolds number at 0.75 r/R
ρ	=	Mass density of water (kg/m^3)
tb	=	maximum propeller blade thickness at 0.75 r/R (m)
T	=	Thrust (N)
V	=	Speed ,velocity (m/s)
V_A	=	Propeller advance speed (m/s)
Z	=	number of propeller blades

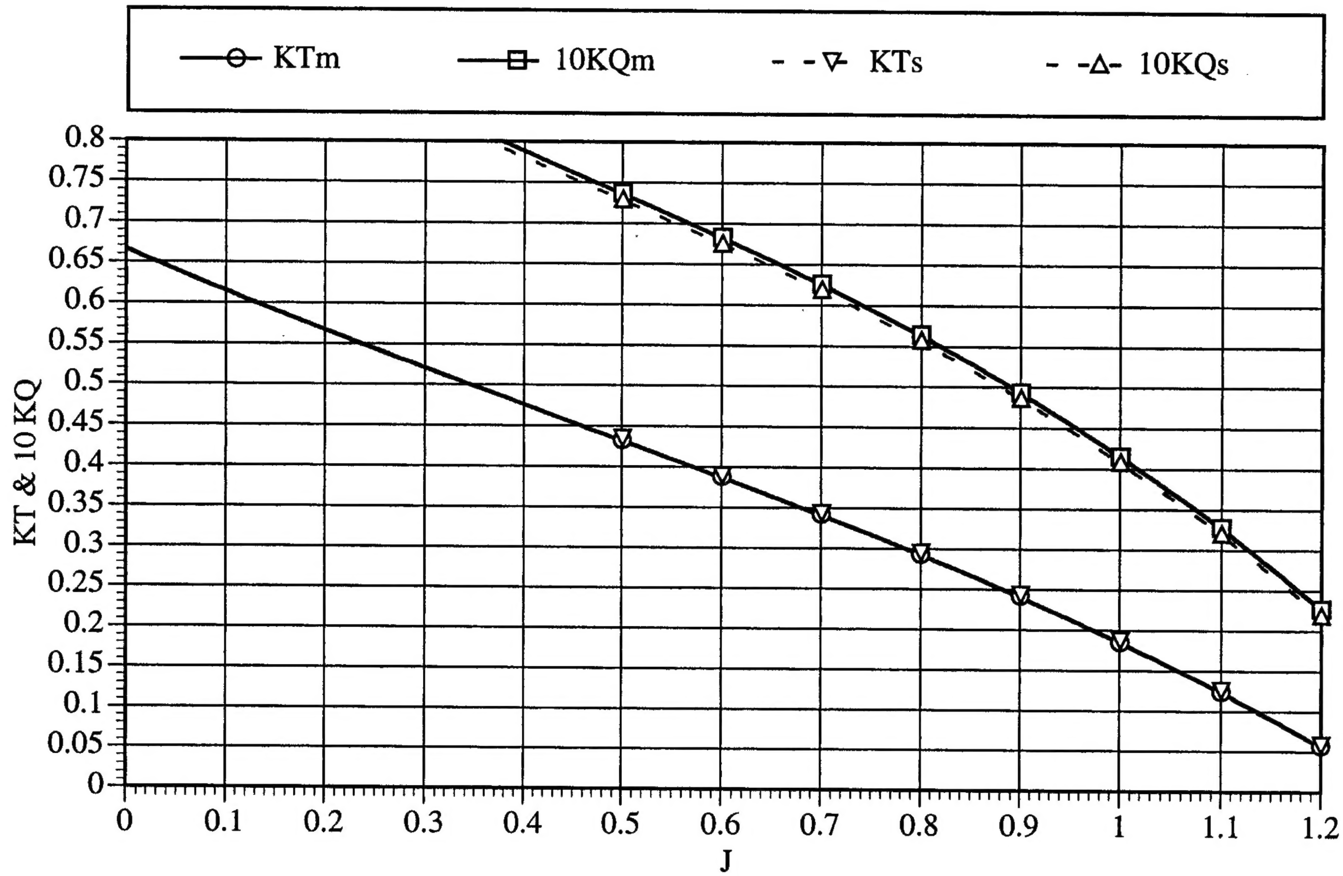

Fig. B2. Model Propeller 5027A Open Water Characteristics and ITTC-78 Corrected Ship Scale Values.

Table B3. Model Propeller 5027A Open Water Characteristics and ITTC-78 Corrected Ship Scale Values.

Model Propeller 5027A characteristics @ r/R = 0.75 :

Z	5	
P/D	1.2282	
c/D	0.39	
t/c	0.0579	
c	2.496	m (ship scale)
kp	0.00003	m (ship scale)
c/kp	83200	
cZ/D	1.95	

J	Uncorrected Model Quantities K_{Tm}	$10K_{Qm}$	K_{Qm}	R_{nco}	C_{Dm}	C_{Ds}
0.50	0.43200	0.73600	0.07360	9.05E+05	0.00879	0.00731
0.60	0.38700	0.68200	0.06820	9.15E+05	0.00878	0.00731
0.70	0.34100	0.62500	0.06250	9.30E+05	0.00877	0.00731
0.80	0.29200	0.56300	0.05630	9.40E+05	0.00876	0.00731
0.90	0.24100	0.49300	0.04930	9.35E+05	0.00876	0.00731
1.00	0.18400	0.41500	0.04150	8.55E+05	0.00884	0.00731
1.10	0.12300	0.32700	0.03270	7.90E+05	0.00891	0.00731
1.20	0.05600	0.22600	0.02260	7.40E+05	0.00896	0.00731

J	ΔC_D	ΔK_T	ΔK_Q	Corrected Ship Quantities K_{Ts}	K_{Qs}	$10K_{Qs}$
0.50	0.00148	-0.00106	0.00072	0.43306	0.07288	0.72877
0.60	0.00147	-0.00106	0.00072	0.38806	0.06748	0.67482
0.70	0.00146	-0.00105	0.00071	0.34205	0.06179	0.61789
0.80	0.00145	-0.00104	0.00071	0.29304	0.05559	0.55594
0.90	0.00145	-0.00104	0.00071	0.24204	0.04859	0.48591
1.00	0.00153	-0.00110	0.00075	0.18510	0.04075	0.40754
1.10	0.00160	-0.00115	0.00078	0.12415	0.03192	0.31921
1.20	0.00165	-0.00119	0.00081	0.05719	0.02179	0.21795

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